CHAPTER 10.5

Tank Leaching

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Tank leaching lies at the core of many hydrometallurgical processes. Leaching is usually performed in mechanically agitated tanks, but there are also alternatives such as pneumatic agitation and jet mixing. Generally, all of a hydrometallurgical plant's revenue is derived from its reactors, and thus even marginal underperformance matters to a plant's economy. The initial investment usually has a low impact on the lifetime costs of typical reactors. Instead, the process result and availability of the equipment make the difference. The hydrometallurgical reactor is not just a mixing tank, and a complete approach requires detailed knowledge of both the process and the equipment.

There is a great variation in tank leaching applications with very different process conditions. Temperatures range from room temperature to over 100°C. Two or three phases can be present, with all kinds of leaching agents and various gases. The required retention time in tank leaching extends from a few minutes to several days depending on the application. This sets some special requirements for reactor design. The process environment can be highly corrosive and abrasive, simultaneous solids suspension and gas dispersion is common, and scaling can be intensive. The most feasible reactor design is always application- and case-specific. There are significant case-by-case variations in the industry's raw materials, processes, and construction material requirements. The cornerstone of successful reactor design is the identification of case-specific critical agitation duties to overcome the factors limiting the reaction rate. In addition, the overall plant unit design, which fulfills the operation, safety, availability, and maintenance aspects, is equally important.

In many hydrometallurgical applications, declining ore grades have forced the use of larger throughputs, leading to higher solution and slurry flows and larger equipment. Larger equipment further emphasizes the importance of accurate reactor specifications to avoid excessive costs through over-dimensioning. With proper reactor design, significant improvement in process performance in terms of energy consumption, gas utilization efficiency, and equipment lifetime can be achieved (Latva-Kokko et al. 2014).

AGITATED TANK LEACHING

The vast majority of industrial leaching operations are performed in mechanically agitated reactors. These devices can be very different in terms of size and construction depending on the application. The smallest reactors are only some cubic meters in volume whereas the largest range up to a few thousand cubic meters. Figure 1 illustrates the different components of a mechanically agitated leaching reactor.

The cylindrical tank with a flat bottom is by far the most commonly used tank design in hydrometallurgy. This is due to its superior mechanical strength against hydrostatic pressure inside the tank that enables minimum wall thickness and use of construction material. In smaller size categories, square and rectangular tanks can also be found. Other tank bottom designs include the dished and cone bottom. In addition, conical fillets that mimic the shape of the dished bottom are being used. These bottom types ease drainage of the tank and can decrease the mixing energy required for solids suspension (Taca and Paunescu 2000). On the other hand, they increase the price of the reactor and decrease the effective slurry volume.

A common height to tank diameter (H/T) ratio is from 1 to 1.5, but much higher ratios can also be used, especially if there is a need to minimize the leaching plant surface area. A high slurry height also generates higher hydrostatic pressure at the bottom of the tank. This improves the leaching kinetics in applications using gas by increasing the solubility of gas in solution, increasing the content of effective molecules in dispersed gas bubbles, and decreasing their maximum stable bubble size (Latva-Kokko and Riihimäki 2012). At H/T ratios of up to 1.2, a single impeller is usually enough to keep the contents well mixed; with higher ratios, two or more impellers are required.

The purpose of baffle plates in leaching tanks is to prevent swirling and vortex formation. They also transform tangential flows into vertical flows, providing top-to-bottom mixing. Baffling also has an effect on the power draw of the impeller. The industrial standard for a wall baffle configuration consists of three or four vertical plates with a width of T/12 or T/10. Plates typically have T/60 spacing to the tank

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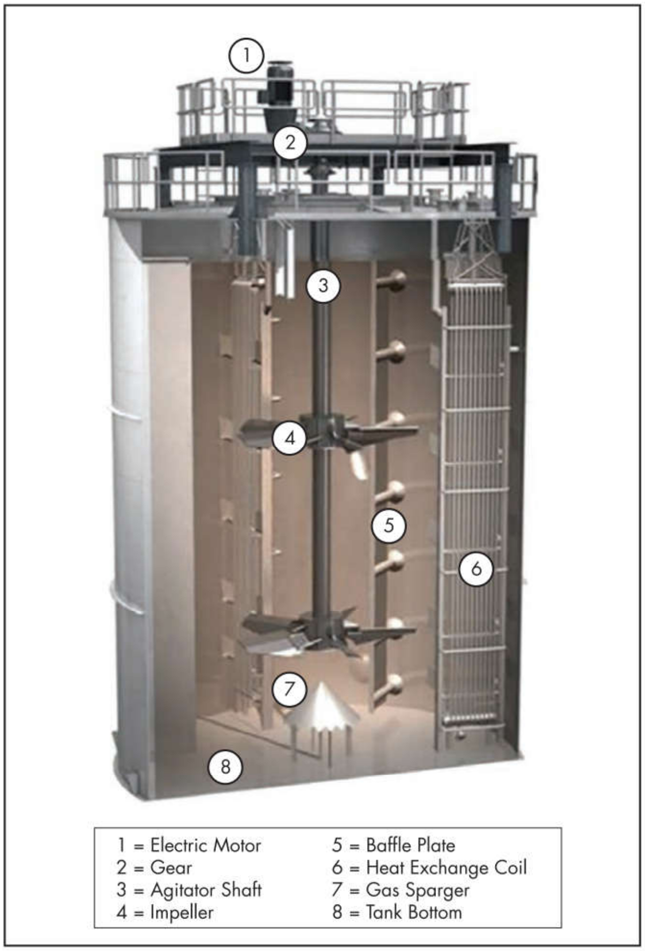

Courtesy of Outotec

Figure 1 Mechanically agitated leaching tank with its components

wall to minimize the dead zones, especially in solid–liquid systems (Hemrajani and Tatterson 2004).

Impellers

The agitator is naturally the most important part of a mechanically agitated tank. A vast variety of different impellers with specific characteristics are available. The selection of an impeller should be made based on the case-specific critical agitation function to optimize reactor performance for any given application. Generally, impellers can be divided into different categories based on their flow pattern, pumping, and shear capabilities. Two main flow patterns, axial and radial, are illustrated in Figure 2. Axial flow impellers have a single up-and-down flow pattern, whereas the radial flow impeller produces two circulating loops, one below and one above the impeller.

Conventional impeller types, such as the propeller, Rushton disc turbine (RDT), and pitched blade turbine (PBT), are still common, but more efficient impellers are available that are specially designed for hydrometallurgical applications. The impellers shown in Figure 3 are categorized according to their flow pattern, pumping, and shear properties. The impeller diameter (D) is typically 0.3 to 0.5 times the tank diameter and the impeller is located less than one D distance from the bottom. If multiple impellers are used, the distance between impellers is usually kept higher than one D.

Agitator Power Draw

The amount of power drawn by an agitator relies on several parameters and is given by:

$$P = N_p \rho N^3 D^5 \quad \text{(EQ 1)}$$

where

P = power
N_p = power number
ρ = mixture density
N = impeller speed
D = impeller diameter

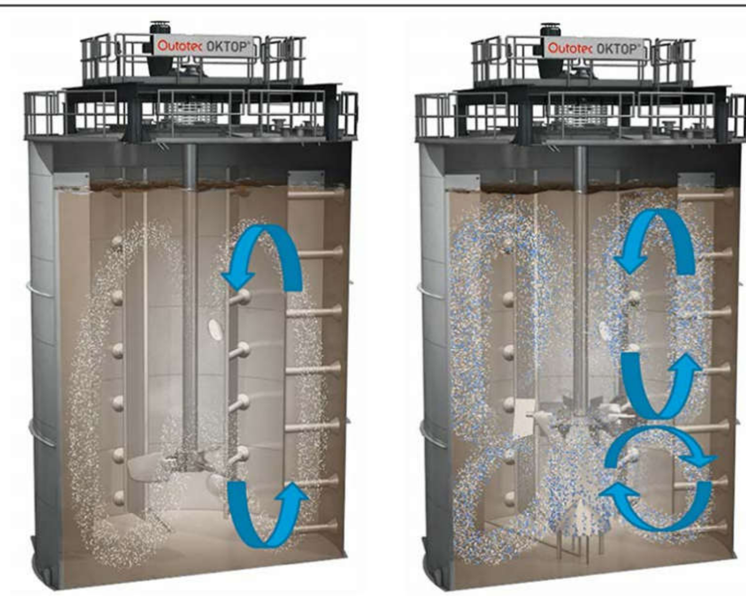

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Figure 2 Axial and radial flow patterns

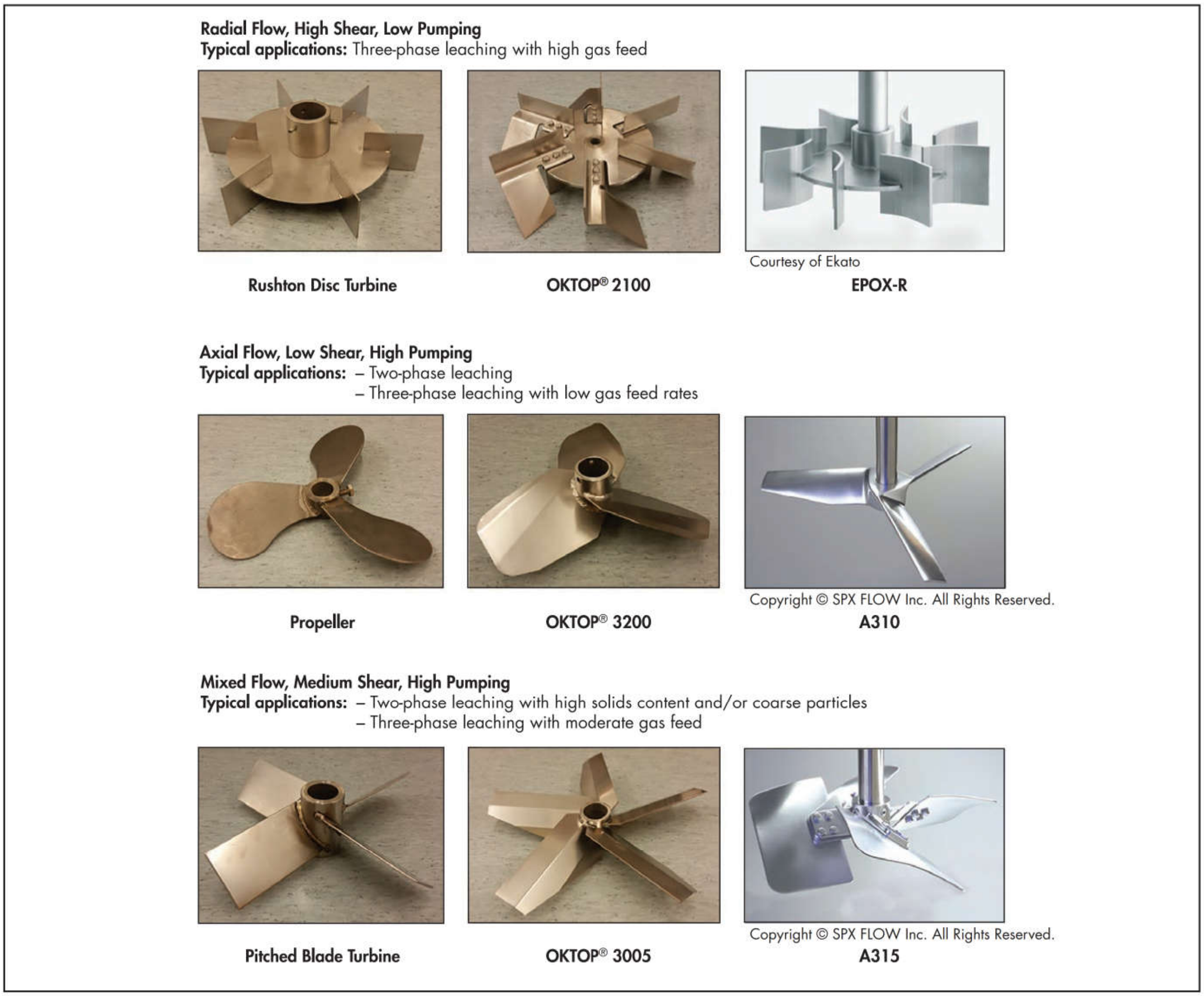


Figure 3 Impeller types categorized according to their properties

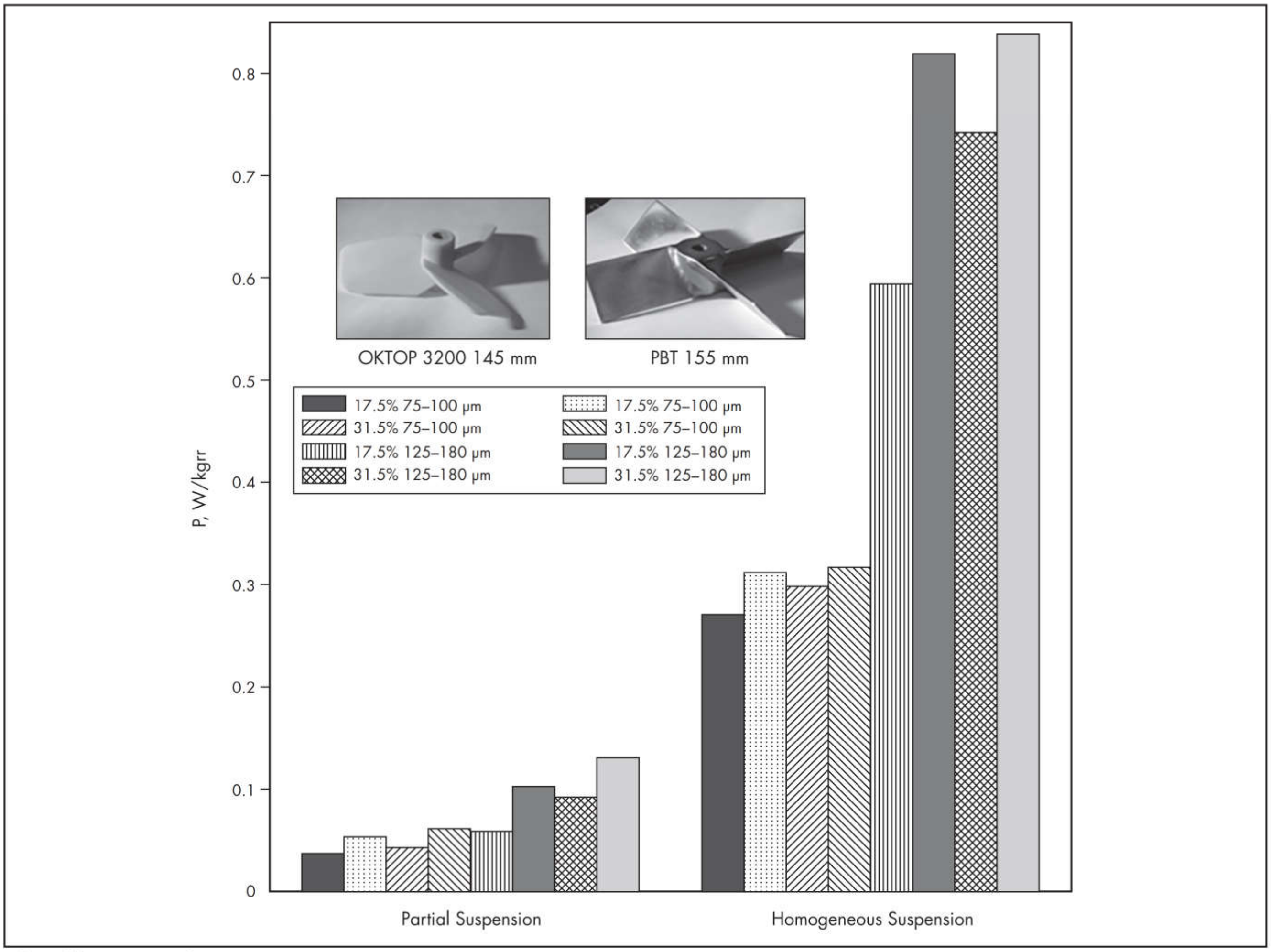
The power number depends on several factors including Reynolds number and impeller characteristics. This formula serves to demonstrate the impact impeller speed and, more particularly, impeller diameter have on an agitator's power draw.

Two-Phase Leaching

In several applications in hydrometallurgy, solids suspension is the main duty of agitation. Leaching processes that do not require gas feed typically belong to this category. Here the leaching rate is often controlled by the chemical reaction rate. In these applications, the process performance of the equipment can be improved by increasing the homogeneity of the suspension. Uniform suspension utilizes the equipment volume fully, providing a longer retention time for solids in a continuous process. Good overall mixing decreases the reagent gradients inside the slurry, which enhances leaching. If the process is known to induce scaling, mixing should be designed to generate higher flow velocities than those required for suspension of the solids alone.

Maximizing the degree of solids suspension with minimal energy consumption has been widely studied (Hosseini et al. 2010; Tahvildarian et al. 2011). The factors that have the largest influence on the required mixing power are the particle size distribution, specific density of solids, and solids content. A typical mixer arrangement in two-phase leaching applications is a downward pumping hydrofoil impeller, which generates a strong axial flow that can carry solid particles close to the surface. Figure 4 shows that off-bottom and uniform solids suspension can be systematically achieved with lower energy consumption by using a wide-blade hydrofoil impeller than by using a standard 45° pitched, four-bladed turbine. This is in good agreement with Wu et al.'s (2006) study on energy efficiency in axial flow impellers, which concludes that PBTs are approximately 7% less efficient than commercial hydrofoil impellers. In addition to impeller type, tank configurations, including baffle plates and the shape of the bottom, have an impact on solids suspension.

The degree of solids suspension has a major effect on the required mixing power, as shown in Figure 4. It is much easier to achieve a partial suspension where all the solids particles are moving than a homogeneous suspension. Liquid to solid mass transfer does not greatly improve as a function of



Adapted from Tervasmäki 2013

Figure 4 Power consumption per total mass of slurry required to achieve partial and uniform suspension with different impellers, solid concentrations (wt %), and particle size fractions. Tests were made with silica sand–water slurry in a flat-bottomed tank with a diameter of 362 mm.

homogeneity after complete off-bottom suspension. However, leaching reactors should always be designed for uniform suspension if they are operated in continuous mode. This is because the retention time of the solid particles can be as much as 40% lower in a reactor series that is being operated in a state of partial suspension compared to uniform suspension.

Three-Phase Leaching

Simultaneous solids suspension and gas dispersion commonly occur in the hydrometallurgical industry. Because of poor oxygen solubility and high oxygen demand, several hydrometallurgical operations are controlled by the rate of oxygen transfer from the gas to the aqueous phase. Among all the factors that affect the rate of oxygen mass transfer, the most important is the reactor configuration and geometry (Filippou et al. 2000). Ideal impellers for gas dispersion are considered to be those that induce radial flow and high shear, such as RDT. However, the presence of gas affects the performance of the impeller and its ability to suspend solids. Thus, three-phase leaching places some special demands on agitator design.

The volumetric mass transfer coefficient, k_La, can be used as a quantitative measure of the mass transfer capability of a reactor. The general equation for the estimation of k_La that is frequently found in the literature follows. It shows that k_La is a function of mixing power intensity (P/V) and superficial gas velocity, v_s. The letters A, B, and C refer to reactor- and application-specific coefficients.

$$k_La = A\,(P/V)^B\,v_s^C \qquad \textbf{(EQ 2)}$$

Impeller performance in a three-phase system is illustrated in Figure 5 with a silica sand, water, and air system. The sand particle size range was between 50 and 200 μm. The solids concentration in these tests was kept at 400 g/L, and the amount of air feed was varied between 0 and 26.5 Nm^3/h. The impeller rotation speed required for complete off-bottom suspension of all solid particles was determined visually.

The selection of an impeller for three-phase leaching applications strongly depends on the type and amount of the gas. If the gas feed rate per reactor volume is low, a downward pumping mixed-flow impeller, such as PBT or OKTOP

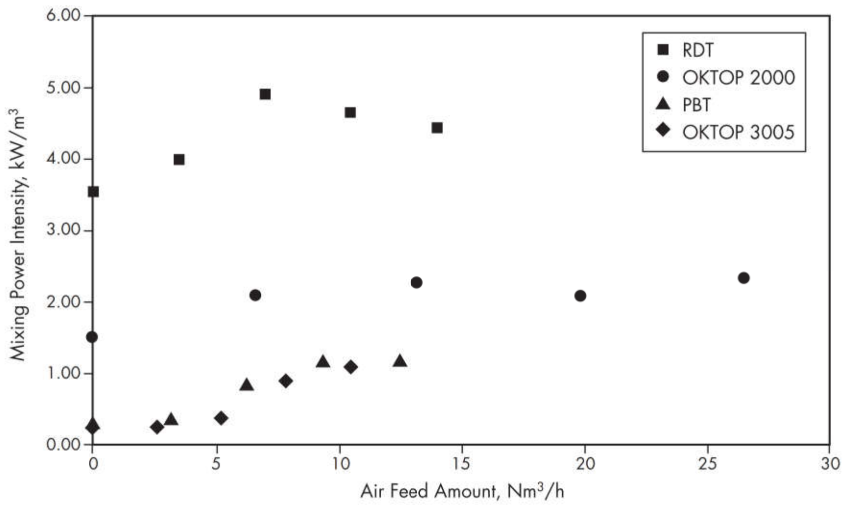


Figure 5 Mixing power intensity required for solids suspension with different impellers in a three-phase model system (400 g/L silica sand 50–200 μm)

3005, is a good choice since it can suspend solids with the lowest mixing power. Mixed-flow impellers offer reasonable pumping efficiency, similar to that of an axial flow impeller, combined with higher shear rates akin to a radial flow impeller. Thus good solids suspension can be achieved while providing reasonable levels of gas dispersion. However, gas feed strongly decreases the PBT's solids suspension performance, making it applicable only with low gas feed rates. These impellers might also be feasible when the gas used is inexpensive, such as air, and it is simply enough to avoid flooding of the impeller. Flooding of the impeller occurs when excessive amounts of gas are handled by the impeller; at this point gas dispersion drops drastically and small bubbles are no longer generated by the shearing action of the impeller.

With large industrial reactors, the speed of the impeller tips is usually the limiting factor, because of erosive wear. Thus, a high power number impeller is required to achieve decent gas dispersion and good gas utilization efficiency at high gas feed rates. As shown in Figure 5, impellers that have a pure radial flow pattern, such as the RDT, require significantly high mixing power to suspend all the particles in the presence of gas. The impeller tip speeds at industrial scale would be extremely high. The OKTOP 2000, an impeller that is specially designed for three-phase systems, can suspend all the solids with a tolerable impeller tip speed at an air feed rate twice as high as any other impeller in this comparison.

Instrumentation and Automation

There are several ways to improve the performance and process control of tank leaching by means of instrumentation and automation. Common instrumentation includes temperature and pH measurements and automated sampling with various metal analyses. It is also possible to monitor and control the solids suspension degree inside a slurry tank. The system includes two integrated measurement probes that are used to monitor the cloud height of the slurry and the thickness of the settled layer of solids at the bottom of the tank. Measurement is based on electrical resistance tomography (Latva-Kokko et al. 2016). For automated control, the mixer motor must be equipped with a variable-speed drive. Because of the rapid development of measurement technologies and data processing capabilities, this aspect is set to become increasingly more important in tank leaching.

OTHER TANK LEACHING SYSTEMS

The vast majority of hydrometallurgical leaching tanks are equipped with top-entry agitators, but there are also other alternatives, some of which are described briefly in this chapter.

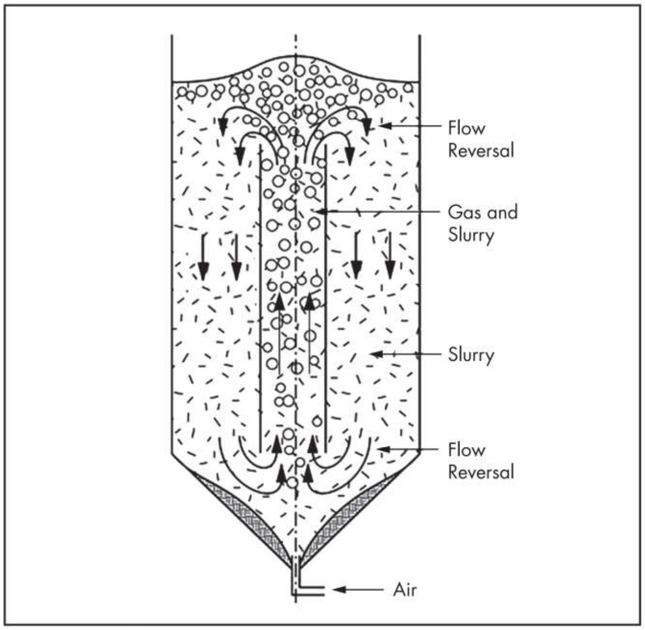
Pachuca Tanks

The Pachuca tank is a large cylindrical vessel with a steep conical bottom. Pachuca tanks typically are 4–10 m in diameter and up to 15 m high. They may also include a central draft tube that can either be short or reach almost to the surface of the tank. Because there is no agitator, to agitate the slurry in the tank, air is injected at the base of the bottom cone as in airlift reactors. Air bubbles carry slurry particles from the bottom of the tank to the surface, as illustrated in Figure 6. From the surface, the slurry flows back through the annular space between the draft tube and tank wall (Mehrotra and Shekhar 2000).

Pachuca tanks have been used in various applications in the minerals industry, such as in the alumina industry and leaching of gold. However, they have been widely displaced by mechanically agitated reactors or draft tube circulators. The main disadvantage of the Pachuca tank is the large quantity of high-pressure air that is required for the agitation. With some ore types there can also be problems with the building up and peeling off of solid masses from the tank walls. The height of the Pachuca tank is another disadvantage and usually necessitates pumping of the pulp. Therefore, the overall energy consumption of a Pachuca tank train is much higher than of mechanically agitated reactors.

Draft Tube Reactors

The draft tube circulator is a reactor configuration where mechanical agitation is enhanced with a draft tube. These reactors typically have a high height-to-diameter ratio of 2:1 or more. The diameter of the draft tube usually ranges from 0.2 to 0.4 times the tank diameter. The impeller is located at



Source: Roy et al. 1998

Figure 6 Operating principle of Pachuca tank

Courtesy of Outotec

Figure 7 Draft tube reactor with bottom-entry agitator

least partly inside the draft tube. The most common design is a top-entry agitator with a downward pumping impeller located at the top of the draft tube. Here the slurry flow is down inside the draft tube and up in the reactor annulus. The flow velocity has to be high enough to avoid sedimentation and lift particles up to the surface. In general, with a draft tube, solids suspension can be achieved with lower mixing power per volume input than in a basic tank. The major limitation of most draft tube circulators is their gas feed capacity, and typically they are not suitable for leaching applications that require large amounts of gas. In addition, the resuspension of settled solids after shutdown can be challenging.

A draft tube circulator that is specially designed for three-phase leaching is shown in Figure 7. Here a bottom-entry agitator is used and the impeller is located at the bottom of the draft tube. The impeller disperses the gas that is introduced below it and induces recirculation through the draft tube so that the direction of flow is downward inside the tube and upward outside of it. These reactors are used for the atmospheric leaching of zinc concentrate. They have a high gas feed capacity and good oxygen utilization efficiency because of the high hydrostatic pressure and local mixing power intensity at the bottom part of the reactor, where most of the gas-to-liquid mass transfer takes place.

Jet Mixing

Mixing of solids requires the input of energy to achieve suspension and, in the case of three-phase leaching, the dispersion of gas. This energy can be implemented mechanically with a rotating impeller or pneumatically as in Pachuca tanks. The third option is to generate a high-velocity jet of fluid with a pump. These jet mixers are not frequently used in leaching applications, but they are common in large storage tanks, where the contents have to be homogenized but the mixing time is not an issue (Grenville and Nienow 2004). Jet mixers do not contain any moving parts inside the tank. They are driven by pumps located on the ground next to the tank. There can be one or several jets in one vessel, and their orientation can be different. Usually, the jet enters from the side of the tank close to the bottom and is directed toward the opposite top corner, as illustrated in Figure 8. However, for leaching applications, a centrally located downward pushing axial jet is the most feasible choice since it suspends solids with the lowest amount of energy.

REACTOR DESIGN

Certain reactor-design-related issues repeat themselves in the hydrometallurgical industry. The faulty selection or improper dimensioning of an agitator leads to a decrease in process performance and availability. Inadequate mechanical design or the wrong material selection may have a considerable impact on the availability, lifetime, and operating cost of the whole reactor system. One of the factors leading to these errors is the cost savings made in the project implementation phase. Another factor may be failing to see the whole picture of the required functions that agitation needs to perform in the process and focusing only on certain aspects of agitation that are considered critical.

Suitable specification material has to be collected to start reactor design. The most notable factors defining reactor design are listed in Table 1. The starting point for reactor design is usually the identification of the reaction limiting factor. Other information collected in the table defines the reactor design leading to required vessel size, agitator type, and possible accessories such as a gas sparger and heating or cooling coils.

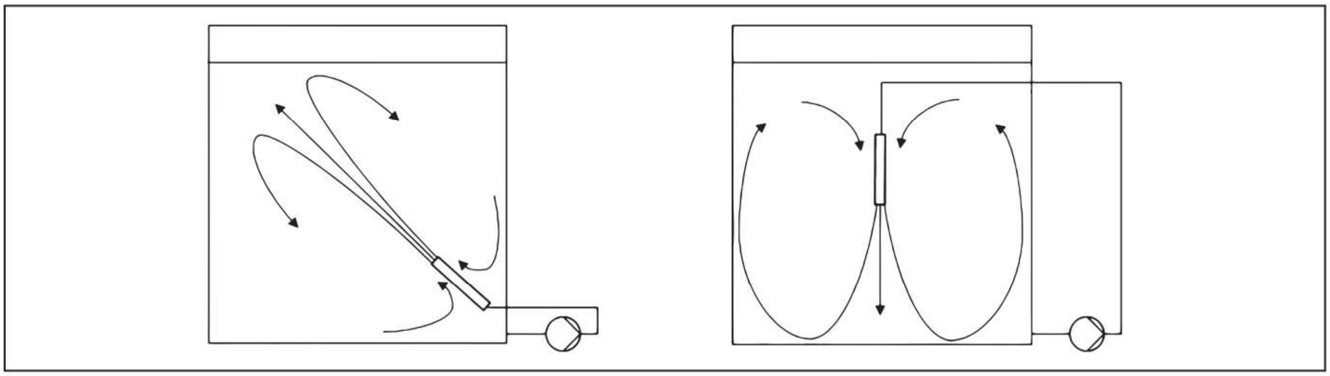


Figure 8 Side entry and axial jet mixing tanks

Table 1 Primary defining factors in stirred-tank reactor design

Factor	Parameters
Reactor duty	Reaction limiting factor, required mixing intensity, critical agitation duty
Solution properties	Mass flow, composition, temperature, density, etc.
Solids properties	Mass flow, density, hardness, particle size
Gas dispersion	Mass flow, density, solubility
Heat transfer	Endothermic or exothermic reaction

Source: Latva-Kokko et al. 2014

Experimental Testing

Adequately performed chemical batch tests with authentic and representative raw material samples create the foundation for successful leaching reactor design. Typically these tests are carried out in 2–5-L reactors in conditions where the reaction rate is not limited by the mixing intensity or the available reactive gas. Thus, an excessive amount of gas feed and oversized mixing intensity are used. These batch tests provide the most feasible process conditions and basic kinetic data for mass and heat balance calculations. Batch test data is converted for a continuous process based on the residence time distribution in a completely mixed stirred tank reactor series (Latva-Kokko et al. 2016).

In some cases, equipment capacity can also restrict the kinetic rate. Usually, limitations in gas feed capacity and solids suspension ability, for instance, are well known by equipment vendors, but their actual effect on the process kinetics should be tested experimentally. These tests must be done on a larger scale, ~20 L, so the industrial process conditions can be scaled down representatively. Ideally, the test equipment is geometrically similar to the industrial design. In addition, the reaction rate limiting factor must be known, since scale-down routines differ by phenomenon. For instance, it might not be possible or feasible to feed as much gas on an industrial scale as has been used in chemical batch tests.

Gas Sparging

Gas feed positioning has an effect on the gas dispersion properties of the tank. Gas is usually fed below the impeller through a sparger. The sparger can be a plain pipe, a ring with a smaller or larger diameter than the impeller, a cone, or a cartwheel-like structure. The purpose of the sparger is to distribute the gas evenly to the impeller. With radial flow impellers there is no need for a special sparger arrangement, since the flow pattern ensures good distribution of gas bubbles. However, a cone sparger can be installed to provide mechanical protection for the gas feed pipe and prevent blocking during shutdown situations. With mixed-flow impellers it is important to feed the gas directly below and rather close to the impeller so that gas bubbles do not bypass the high shear zone of the impeller in the rising fluid flow. Gas may also be introduced down the shaft of the agitator (using a rotating joint at the top of the shaft), exiting the bottom of the shaft at a point below the lower impeller. This method is commonly used in gold leaching (carbon-in-leach or carbon-in-pulp) applications where air (or oxygen) is used to enhance leaching kinetics.

The gas-to-liquid mass transfer can also be increased by using high-velocity gas feed spargers. These devices feed gas at so-called supersonic speed, that is, more than 400 m/s. A high-velocity gas jet creates high local shear rates that induce fine bubbles. Obtaining a high gas feed velocity requires a high gas pressure, and because use of a compressor creates more sources for energy losses, they are less economical than direct dispersion of gas with an agitator (Jung and Keller 2016). In addition, there are some nozzle wear and blocking issues in the use of these high-velocity gas feed spargers.

Mechanical Issues

Many things can go wrong in the mechanical design of an agitator. The shaft may be too narrow or too thin so that it bends in operation. On the other hand, a very hard and rigid shaft can break under heavy loads, such as those during start-up situations. Even a small dissymmetry in impeller blades or simply operating at resonance frequency may cause severe vibration of the whole reactor. Perhaps the most challenging aspect of mechanical design is the long-term endurance of the agitator. During operation, impeller blades are exposed to severe fatigue stress and wear by the combined effect of corrosion and abrasion. Usually, the corrosion resistance of a stainless steel weld is not as high as that of the base material.

In addition to corrosion, the welded joints of impellers are vulnerable to fatigue failure. Welded joints can thus be considered as the weakest link of an impeller. An agitator design that does not contain any welded joints of impeller blades or their fastenings is superior to welded structures in terms of corrosion resistance and mechanical strength. It also enables easy and quick replacement of worn-out blades with new ones. Figure 9 shows a series of impellers that do not contain any welded joints.

Figure 9 Impellers containing no welded joints and their welded duplicates

Construction Materials

Highly corrosive and abrasive conditions are often present in tank leaching. Therefore, the selection of materials is a crucial part of reactor design. The starting point for case-specific material selection is the corrosion resistance of the material under process conditions. The temperature and chemical composition determine the corrosivity of the solution. In hydrometallurgical applications, both uniform and localized corrosion must be taken into account. Uniform corrosion typically occurs in acids and hot alkaline solutions. Localized corrosion, such as pitting or crevice corrosion, is of concern in acidic solutions that contain chloride ions and oxidizing ions like Fe^{3+} (Latva-Kokko et al. 2014).

Stainless steels traditionally have been a common construction material for hydrometallurgical reactors. Austenitic steel grades such as 316L (1.4432) and 904L (1.4539) are typical choices thanks to their good fabrication characteristics. Of these grades, the higher alloyed 904L is more corrosion resistant. Duplex steel grades that have an austenitic-ferritic structure provide excellent corrosion resistance together with higher mechanical strength and surface hardness (Ekman and Berqvist 2008). Results from some corrosion tests are presented in Table 2.

As shown in Table 2, the different metal ion contents in solution greatly impact the corrosion resistance of different stainless-steel grades. In atmospheric operation, even higher corrosion resistance can be achieved by the use of fiberglass-reinforced plastic, which is able to withstand very high chloride content. In oxidizing conditions, titanium and its alloys can provide excellent corrosion resistance even in hot, acidic, and chloride-rich environments (Laihonen and Lindgren 2013).

Leaching reactors are also exposed to erosive wear because of the high solids content and abrasive components found in many ores and concentrates. Impeller blades in particular tend to wear because the velocities of the particles are highest next to the impeller. Impact and sliding wear are the two main wear mechanisms in impellers, and the erosion rate is strongly dependent on the impeller tip speed (Keller 2007). In addition to impeller tip speed, factors that most affect the intensity of erosive wear are solids content, particle size and shape, particle specific density, and hardness. Impeller blades, hubs, and shafts are often protected from wear through the use of polymeric coatings. Rubbers (either natural or synthetic) or polymers such as polyurethane are used to protect agitator components from wear.

Tank Leaching Plant

When developing a leaching plant, the correct specification of the reactor and agitator is only a part of the work required for successful operation. When multiple reactors form a plant unit and plant units form a complete plant, a comprehensive design is required to achieve a solution that has the required operation and maintenance design factors implemented.

In hydrometallurgical reactor design, it is common practice to comply with industry-specific standards, so process-specific requirements are not the main focus. Reactors in a certain process area should be seen as part of a larger reactor plant unit that includes, in addition to the reactor solution, transfer systems, access platforms, piping, and electrification. In addition to metallurgical performance, plant design should secure high availability with safe and easy operation and maintenance.

One of the key features in leaching plant design is connecting reactors in series. Inlet or outlet pipes must be designed

Table 2 Results from corrosion tests conducted at 90°C with different stainless-steel grades

		Austenitic 316L		LDX 2101		Duplex 2205	
Solution	Cl^-, mg/L	mm/yr*	Loc.†	mm/yr	Loc.	mm/yr	Loc.
10 g/L H_2SO_4	200	0.80	Yes	<0.01	No	<0.01	No
10 g/L H_2SO_4, 0.1 g/L Cu^{2+}	200	<0.01	No	<0.01	No	<0.01	No
10 g/L H_2SO_4, 1.0 g/L Cu^{2+}	200	<0.01	No	<0.01	No	<0.01	No
10 g/L H_2SO_4, 10 g/L Cu^{2+}	200	<0.01	No	<0.01	No	<0.01	No
10 g/L H_2SO_4, 0.1 g/L Fe^{2+}	200	<0.01	No	<0.01	No	<0.01	No
10 g/L H_2SO_4, 1.0 g/L Fe^{2+}	200	0.03	No	<0.01	No	<0.01	No
10 g/L H_2SO_4, 10 g/L Fe^{2+}	200	<0.01	No	<0.01	No	<0.01	No
10 g/L H_2SO_4, 0.1 g/L Fe^{3+}	200	0.01	No	0.01	No	<0.01	No
10 g/L H_2SO_4, 1.0 g/L Fe^{3+}	200	0.17	Yes	0.21	No	<0.01	No
10 g/L H_2SO_4, 10 g/L Fe^{3+}	200	0.84	Yes	<0.01	No	<0.01	No

Source: Latva-Kokko et al. 2014
*mm/yr = Uniform corrosion rate in millimeters per year (if <0.1 mm/yr, material is corrosion resistant).
†Loc. = Localized pitting or crevice corrosion occurs (yes/no).

Courtesy of Outotec

Figure 10 Gravity flow launder connecting reactors in series

to avoid short circuiting flows. With a traditional overflow channel between the tanks, there is a high probability that part of the slurry will bypass the main reactor volume. Especially with sulfidic particles that are hydrophobic by nature and tend to form a froth layer at the tank surface, there can be a significant decrease in leaching yield if an overflow connection is used. Pipes that connect reactors clearly below the surface are a better option, but usually not very flexible. A gravity flow launder with inlet and outlet pipes, as shown in Figure 10, provides easy bypass of any or even several reactors at the same time for maintenance.

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